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Limnological Comparison of Culturally Eutrophic Shagawa Lake and Adjacent Oligotrophic Burntside Lake, Minnesota

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INTRODUCTION

Although oligotrophic lakes dominate northeastern Minnesota, Shagawa Lake, St. Louis Co., Minn., has attained high levels of algal productivity. This cultural eutrophication resulted primarily from the high amounts of nutrients discharged from the waste-water treatment plant operated by the City of Ely (Malueg *et al.*, 1975). Pilot studies conducted from 1966 to 1970 demonstrated that removing phosphorus from the waste water entering the lake would limit the amount of algal production (Smith, 1973). Subsequently, in order to demonstrate lake restoration by removing one critical nutrient, the city constructed a tertiary treatment plant to remove more than 99% of the phosphorus from all municipal waste-water effluent.

This paper compares the limnological characteristics of Shagawa Lake with the immediately upstream, oligotrophic Burntside Lake during 1971 and 1972, just prior to the January 1973 initiation of tertiary treatment. Because Burntside Lake remains minimally influenced by man, this nearly pristine lake will serve as a control for future evalua-

tions on how well tertiary waste-water treatment has restored Shagawa Lake.

Geology, basin morphology and watershed flora.—Both lakes lie in a watershed (Fig. 1) classified geologically as a bedrock basin (Zumberge, 1952). The surface geological formation—an early Precambrian, igneous metamorphic complex—resists erosion and leaching by surface water. The drainage basin, excluding Burntside and Shagawa lakes, covers 231 km² with 100 km² lying downstream from the Burntside Lake outlet. The drainage area between Burntside Lake outlet and Shagawa Lake is 38 km².

Both lakes are characterized by steep shorelines, irregular bottoms and many islands (Table 1). Burntside Lake lies in a deep basin with a maximum depth ca. 49 m, whereas the Shagawa Lake basin is relatively shallow with a maximum depth ca. 14 m. The surface area of

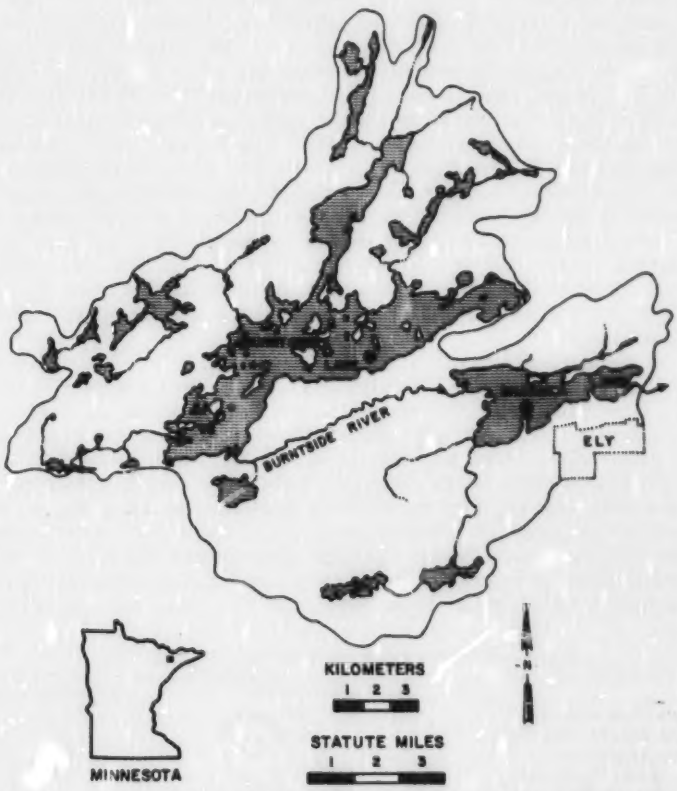

Fig. 1.—Watershed area. Sampling stations shown as ●

Burntside Lake is about three times greater than that of Shagawa Lake and the volume about eight times greater.

The dominant flora of the watershed is composed of a generally dense deciduous and coniferous forest of quaking aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), black ash (*Fraxinus nigra*), paper birch (*Betula papyrifera*), balsam fir (*Abies balsamea*), black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*). Because of extensive logging around Shagawa Lake, the forest consists of second-growth trees.

Climate.—During 1971 and 1972, average annual precipitation was 64 cm, about 70% falling during the open water seasons and the rest falling when ice covered the lakes. Ice covered Shagawa Lake from mid-November through mid-May, while freezing and thawing dates for Burntside Lake were 7-10 days later. By late winter, both lakes had ice 75-90 cm thick.

Cultural history.—In 1883 rich deposits of iron ore were discovered near the southern shore of Shagawa Lake. By 1888, a village had formed with a population of 104 persons. Five mines operated by 1900, and 3717 persons lived in the newly incorporated City of Ely. In 1901 the city began discharging untreated municipal waste water directly into Shagawa Lake. Primary treatment using Imhoff tanks to remove solids began in 1912 and continued until 1954. Then the addition of a high rate trickling filter provided secondary treatment to reduce organic loading to the lake, although only minimally affecting phosphorus and nitrogen loading. As mining operations decreased, the population correspondingly declined from its 1930 maximum of 6151 to about 5000 persons today. The last mine closed in April 1967. Today the major industry in Ely is tourism, due to its proximity to the Boundary Waters Canoe Area.

Hydrology.—Eight tributaries, some intermittent, drain the Burntside Lake watershed (Fig. 1). Burntside River, the only outlet of Burntside Lake, enters the NW end of Shagawa Lake about 10 river km downstream and accounts for about 65% of the annual water input to Shagawa Lake. Four small tributaries, one intermittent, account for approximately 19% of the Shagawa Lake water input. The treated waste-water effluent, entering Shagawa Lake midway along the southern shore, accounts for approximately 2% of the annual water input. The U.S. Geological Survey installed groundwater observation wells around Shagawa Lake in 1970 and determined that groundwater is not a significant factor in the hydrology of the lake. Since bedrock under-

TABLE 1.—Morphology of Shagawa and Burntside lakes

	Shagawa Lake	Burntside Lake
Watershed area (km^2)	100.	131.
Lake surface area (km^2)	9.2	29.2
Mean depth (m)	5.7	15.2
Maximum depth (m)	13.7	48.8
Volume (km^3)	0.053	0.44

lies both lakes, groundwater (if any) would be restricted to structural fractures. Shagawa River is the only outlet of Shagawa Lake.

The outlet flow and lake volume indicate that the hydraulic residence time for Burntside Lake was approximately 7.5 years during the study period. The residence time for Shagawa Lake was 0.65 year and seasonally ranged from approximately 2 months during high runoff periods to 2 years during the low flow winter months.

METHODS AND MATERIALS

Three stations routinely sampled in Shagawa Lake showed only a slight gradient in limnological characteristics from inlet to outlet. Therefore, only the central deep station with a depth of 13.7 m will be compared limnologically to a central deep site of about 24 m in Burntside Lake (Fig. 1).

Whereas Shagawa Lake was sampled weekly, Burntside Lake was sampled monthly in 1971 and biweekly in 1972. Both lakes were sampled at the surface and vertically to the bottom at 1.5-m intervals. Most limnological parameters reported here are based on data from samples taken 1.5 m below the surface (upper water) and 1.5 m above the lake bottom (lower water).

Specific conductance, *p*H, temperature and dissolved oxygen were measured *in situ* with a Martek Mark II* water quality analyzer. Water transparency was measured with a submarine photometer and a 20-cm black and white Secchi disc. Water samples for chemical and algal analyses were obtained with a 4-liter PVC Van Dorn sampler.

In 1971 the samples for nitrogen and phosphorus were preserved with $HgCl_2$ immediately after collection and sent to the EPA, Pacific Northwest Environmental Research Laboratory in Corvallis, Oregon, for analyses. In 1972 samples were not preserved and were analyzed in Ely the same day they were collected. Analyses were performed using Environmental Protection Agency methods (1971).

Major cations (Ca^{++}, Mg^{++}, Na^{+} and K^{+}) were sampled monthly in Shagawa Lake and bimonthly in Burntside Lake, while trace metals (Co, Cu, Mo, Zn, Fe and Mn) were sampled quarterly in Shagawa Lake, and in the summer in Burntside Lake. All were analyzed using atomic absorption spectrometry.

Sediments were collected four times a year with an Ekman dredge at the 6-m and 13.5-m depths in Shagawa Lake, and at the 10-m and 23-m depths in Burntside Lake. The top few centimeters were removed from the sample and dried at 103 C overnight. The dried sample was analyzed for total carbon and nitrogen using a Hewlett-Packard Model 185 B, C-H-N Analyzer* and for total phosphorus by persulfate/sulfuric acid digestion. Another dredge sample was completely mixed and interstitial water obtained by pressure squeezing through a 0.45 μ membrane filter.

*Mention of commercial products does not constitute endorsement or recommendation by the Environmental Protection Agency.

Algal samples were identified and enumerated using the "clump count" method with a Sedgwick-Rafter counting chamber. Chlorophyll *a* was determined using the UNESCO method (1966).

Zooplankton was sampled with a #20 mesh Wisconsin net vertically hauled 13.5 m in Shagawa Lake and 22.5 m in Burntside Lake. Total catch was converted to organisms/liter based on the amount of water that theoretically passed through the net. Benthos was sampled monthly with an Ekman dredge (15 × 15 cm) at the two stations and separated from the mud using a U.S. Series Equivalent 40 sieve.

RESULTS

PHYSICAL PARAMETERS

Temperature.—Shagawa and Burntside lakes are dimictic lakes with spring and autumn mixing (Fig. 2). Generally a summer thermocline began to develop in Shagawa Lake in early June and continued until late August. During August, the thermocline had a temperature gradient of about 0.5 C per m and approached a depth of 10 m with about 1% of the lake volume remaining below this depth. Its destruction by a weather cold front in 1971 (winds >32 km/hr and air temperature 7 C below the monthly average) demonstrated the instability of the stratification. After calm conditions returned, stratified conditions developed. In Burntside Lake, the thermocline began developing in early June, continuing until early September when it reached 7-8 m deep. During August, its temperature gradient was about 1 C per m. In contrast to Shagawa Lake, the weather cold front in 1971 did not destroy stratification but did depress the thermocline.

During stratification the maximum temperatures in the upper water were 21 C and 20.5 C for Shagawa and Burntside lakes, respectively. The corresponding maximum temperatures in the lower water ranged from 12-14 C and from 8-9 C. Autumn circulation began in mid-September in Shagawa Lake, but not until late October or early November for Burntside Lake.

Water transparency.—In Shagawa Lake the maximum Secchi disc depth in 1972 was 6 m just prior to ice cover and a minimum depth of <1 m was observed during summer blue-green algal blooms. The depth of the 1% light level ranged from 2.5 m in September to 5.5 m in late October. In Burntside Lake, Secchi disc transparency in 1972 ranged from 7 m just prior to ice cover to 3.5 m in mid-September while the depth of the 1% light level during the ice-free period ranged from 8 m in August to 9.5 m in July.

CHEMICAL PARAMETERS

Dissolved oxygen.—Because of a questionable sampling technique for dissolved oxygen, values for the lower waters of both lakes should be considered approximations (± 0.5 mg/l) and not absolute values for the early part of 1972. The lower water of Shagawa Lake became

anaerobic during winter and summer stratification (Fig. 2), while the lower water of Burntside Lake remained aerobic throughout the year. The lowest value for Burntside Lake at 21 m was about 4 mg/liter, although oxygen levels as low as 1 mg/liter were recorded at the deepest hole. The upper water of Shagawa Lake became supersaturated with oxygen during summer periods of high algal activity, peaking at 12.2 mg/liter (136% of saturation) in mid-June 1971 during a diatom bloom. In Burntside Lake, dissolved oxygen was above saturation only

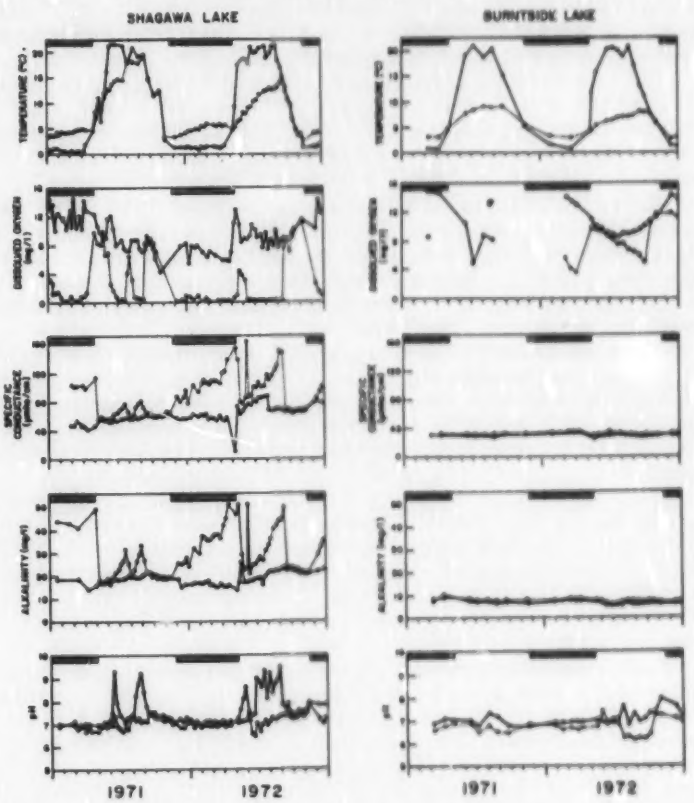

Fig. 2.—Physical and chemical characteristics of Shagawa and Burntside lakes for 1971 and 1972.
—○———○— = upper water (1.5 m)
---●------●--- = lower water (12 m in Shagawa Lake, 23 m in Burntside Lake)
* approximate dissolved oxygen concentration
bars across top of graphs represent ice cover

occasionally in winter and shortly after ice breakup.

Specific conductance.—Specific conductance ranged from about 40 to 160 μmho/cm at 25 C in Shagawa Lake and averaged about 65 μmho/cm during autumn circulation (Fig. 2). Specific conductance in Burntside Lake was almost constant at about 40 μmho/cm.

Total alkalinity.—Total alkalinity (as $CaCO_3$) and specific conductance were closely related in both lakes. In the lower water of Shagawa Lake, alkalinity increased from about 20 to 50 mg/liter during anaerobic periods, but remained fairly constant at 18-22 mg/l in the upper water (Fig. 2). In Burntside Lake, total alkalinity remained constant at about 10 mg/liter for all depths.

*p*H.—In Shagawa Lake the upper water *p*H changes were related to algal activity and often exceeded 9.0 during algal blooms (Fig. 2). Winter values generally were 7.0. The *p*H in Burntside Lake also peaked when algal activity was most intensive in December, but only reached a maximum value of 7.9. Winter values were about 6.9.

Phosphorus.—In the upper water of Shagawa Lake, the orthophosphate phosphorus decreased to undetectable levels (<0.001 mg/l) during early to midsummer, while total phosphorus increased during this period (Fig. 3). Increased total phosphorus concentrations in the lower water, principally in the orthophosphate phosphorus form, corresponded to anaerobic conditions.

Total phosphorus in both upper and lower waters of Burntside Lake fluctuated between 0.004 and 0.012 mg/liter with no apparent correlation with other measured parameters. Orthophosphate phosphorus generally was at the minimum detectable limit (0.001 mg/liter) except in spring when it increased to about 0.005 mg/liter in the lower water.

Nitrogen.—Nitrate in the upper water of Shagawa Lake decreased during the summer (Fig. 3). During the ice-covered interval, nitrate concentrations in both upper and lower waters increased to 0.15-0.20 mg/liter from an autumn value of <0.01 mg/l. Ammonia generally was below detectable limits (0.01 mg/l) in the upper water while in the lower water it increased under ice cover to 0.5 mg/liter and in late summer to 1.0-1.7 mg/liter.

During the early part of the growing season, nitrate in the upper water of Burntside Lake decreased from 0.05 mg/liter to undetectable values (0.01 mg/liter) and remained there until autumn. Ammonia concentrations generally were less than 0.01 mg/liter but reached high values of 0.24 and 0.13 mg/liter in the upper water during August 1971 and September 1972, respectively. Similarly, 0.13 mg/liter was the maximum ammonia concentration in the lower water in September 1972. Nitrate in the lower water ranged from undetectable values to 0.1 mg/liter with the maximum values occurring during the winter.

Major cations.—The order of abundance of the major cations in both Shagawa and Burntside lakes was $Ca^{++} > Mg^{++} > Na^{+} > K^{+}$. Average concentrations of calcium, magnesium and sodium in Shagawa Lake were about double those of Burntside Lake, while potassium

concentrations in Shagawa Lake were slightly less in the upper water and greater in the lower water than those observed in Burntside Lake (Table 2). Shagawa Lake cation concentrations were higher in the lower water during periods of stratification. Concentrations in Burntside Lake were almost identical in the upper and lower waters throughout the two years. Both Shagawa and Burntside lakes had

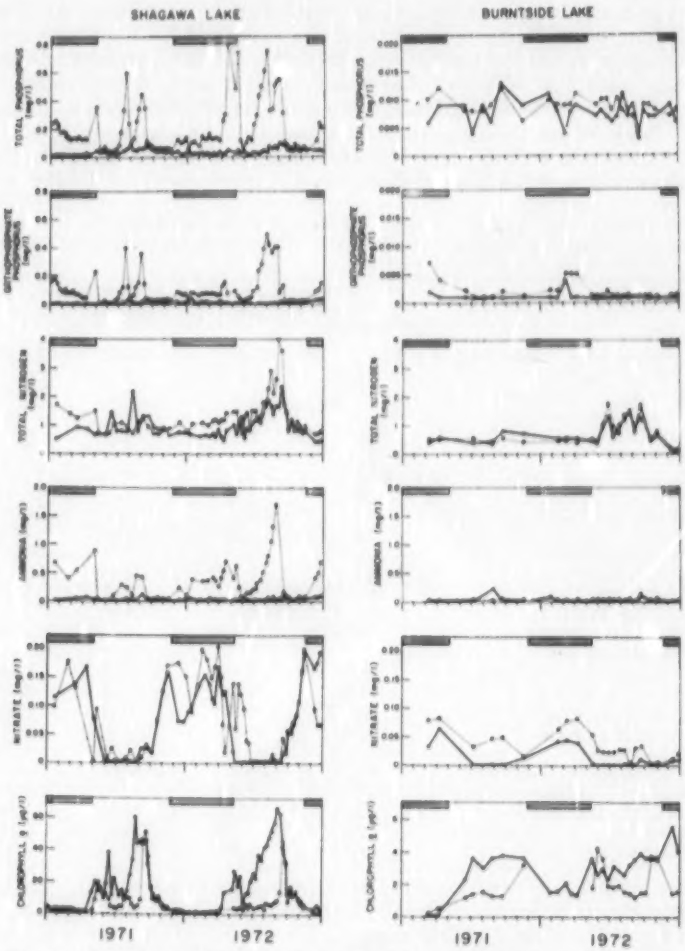

Fig. 3.—Chemical and biological characteristics of Shagawa and Burntside lakes for 1971 and 1972. Symbols same as Figure 2

lower cation concentrations in the upper water than Bright (1968) observed for 19 nearby lakes, but higher values than reported by Armstrong and Schindler (1971) for 40 lakes located in the Canadian Shield of Ontario, Canada (Table 2).

Trace metals.—Trace metal (Co, Cu, Fe, Mn, Mo and Zn) concentrations were higher in Shagawa Lake than in Burntside Lake (Table 2). Especially noticeable in high concentrations were iron and manganese, either reflecting sump water discharged to the lake from the iron mines during mining operations or derived from the geological formation in the immediate area. During anaerobic conditions in the lower water of Shagawa Lake, iron increased to a maximum of 10,300 μg/liter and manganese to a maximum of 2200 μg/liter.

Lake sediment.—Shagawa Lake sediment had higher concentrations of nutrients in both the dried sediment and interstitial water than found in Burntside Lake sediment (Table 3). The greatest observed difference

TABLE 2.—Comparison of mean values of various parameters in the upper and lower waters of Shagawa and Burntside lakes during 1971-1972, with means of Ontario lakes and Minnesota lakes

Parameter	Shagawa Lake		Burntside Lake	
	1.5m	12m	1.5m	21m
Specific conductance (μmho/cm)	51.5	73.1	32.7	31.2
Calcium (mg/liter)	7.6	10.3	3.3	3.3
Magnesium (mg/liter)	2.0	2.3	1.1	1.0
Sodium (mg/liter)	1.4	1.8	1.0	0.9
Potassium (mg/liter)	0.6	0.8	0.7	0.5
Iron (μg/liter)	189	1640	29	70
Manganese (μg/liter)	23	526	6	12
Silica (mg/liter)	2.9	6.8	1.5	2.5
Sulfate (mg/liter)	10	10	10	10
Chloride (mg/liter)	2.3	3.1	3.0	1.7
Cobalt (μg/liter)	2	2	1	2
Copper (μg/liter)	3	3	2	2
Molybdenum (μg/liter)	13	13	8	8
Zinc (μg/liter)	9	10	8	7
Total phosphorus (mg/liter)	0.038	0.185	0.008	0.009
Orthophosphate phosphorus (mg/liter)	0.012	0.107	0.003	0.002
Total-N (mg/liter)	1.03	1.26	0.70	0.69
Ammonia-N (mg/liter)	0.032	0.317	0.027	0.018
Nitrate-N (mg/liter)	0.061	0.066	0.012	0.036
pH	7.51*	7.07*	7.14*	6.72*
Total alkalinity (mg/liter)	18.9	28.2	7.6	7.1
Seston dry weight (mg/liter)	2.0	3.8	0.8	0.6
Chlorophyll *a* (μg/liter)	14.8	7.0	2.8	1.8
Phaeophytins (μg/liter)	1.9	2.5	0.6	0.8
Dissolved oxygen	10.4	2.9	10.4	8.8

was in the phosphorus content, a concentration 13 times greater in the deep station interstitial water of Shagawa Lake than at the deep station in Burntside Lake. Nutrient concentration in Shagawa Lake sediments increased with lake depth, while concentrations were fairly equal at both depths in Burntside Lake.

BIOLOGICAL PARAMETERS

Chlorophyll a.—In Shagawa Lake, a spring bloom of green algae (1971) and diatoms (1972) developed about the time of ice breakup and increased the chlorophyll *a* concentration at the 1.5-m depth from about 1 μg/liter to 20 μg/liter (Fig. 3). In late summer, the chlorophyll *a* concentration reached 50-60 μg/liter during blue-green algae blooms. In late summer and early autumn, chlorophyll *a* values rapidly decreased to their lowest values of the year, stabilizing at

TABLE 2.—(continued)

	Mean for 40 Ontario lakes (Armstrong and Schindler, 1971) euphotic zone	Mean for 19 NE Minnesota lakes (Bright, 1968) 0.5 m
Specific conductance (μmho/cm)	21*	....
Calcium (mg/liter)	1.6	10.2
Magnesium (mg/liter)	0.9	3.0
Sodium (mg/liter)	0.9	1.6
Potassium (mg/liter)	0.4	0.8
Iron (μg/liter)	50**	94
Manganese (μg/liter)	....	16.8
Silica (mg/liter)	....	5.57
Sulfate (mg/liter)	3.0	5.8
Chloride (mg/liter)	1.4	0.13
Cobalt (μg/liter)	....	....
Copper (μg/liter)	....	3.2
Molybdenum (μg/liter)	....	2.0
Zinc (μg/liter)	....	11.6
Total phosphorus (mg/liter)	0.007**	0.0046
Orthophosphate phosphorus (mg/liter)	....	....
Total-N (mg/liter)	0.177**	....
Ammonia N (mg/liter)	....	....
Nitrate-N (mg/liter)	....	....
pH	....	7.56
Total alkalinity (mg/liter)	....	....
Seston dry weight (mg/liter)	....	....
Chlorophyll *a* (μg/liter)	3	....
Phaeophytins (μg/liter)	....	....
Dissolved oxygen	....	....

* Median
** Total dissolved

TABLE 3.—Sediment analyses

	Shagawa Lake		Burntside Lake	
	6m	13.5m	10m	23m
Dried sediment (g/kg)				
Phosphorus	5.3	8.4	2.9	1.9
Nitrogen	14.3	16	10.7	10.5
Carbon	116	125	90	94
Interstitial water (mg/liter)				
Total soluble phosphorus	0.32	1.47	0.12	0.11
Inorganic nitrogen	0.67	1.04	0.99	1.24

a low 1 μg/liter throughout the winter. In Burntside Lake, maximum chlorophyll *a* concentrations of 4-6 μg/liter were observed in late

TABLE 4.—Phytoplankton found during 1971 and 1972 at the 1.5-m depth

Genera	Shagawa Lake	Burntside Lake
I. Blue-green		
Anacystis spp.	+	+
Anabaena spiroides	++	+
A. circinalis	+++	+
Anabaena spp.	—	+
Aphanizomenon flos-aquae	++++	+
Coelosphaerium naegelianum	+++	+
Chroococcus spp.	+	++
Gloetrichia echinulata	+	—
Coelosphaerium spp.	+	+
Oscillatoria spp.	+	+
Schizothrix calcicola	++	+
II. Green		
Ankistrodesmus spp.	++	+
Botryococcus spp.	—	+
Chlamydomonas spp.	—	+
Chlorella-type	+++	+
Chlorogonium spp.	++	—
Closterium spp.	+	—
Coelastrum spp.	+	—
Cryptoglena pigra	++	+
Dictyosphaerium pulchellum	+	+
Euglena spp.	+	+
Lagerheimia spp.	—	+
Oöcystis spp.	+	+
Schroederia spp.	++	+
Trachelomonas spp.	+	++
Trochiscia spp.	++	—
Ulothrix spp.	+	—
III. Diatoms		
Asterionella spp.	++++	+
Cyclotella spp.	+	+
Fragilaria spp.	++++	+
Melosira spp.	++	+
Navicula-type	+	+
Rhizosolenia spp.	++	+
Stephanodiscus niagarae	++	—
Synedra spp.	+++	++
Tabellaria spp.	+	+
IV. Other pigmented flagellates		
Ceratium hirundinella	+	+
Chrysosphaerella spp.	+	+
Dinobryon bavaricum	+	+
D. sertularia	+	+

— not found at the 1.5-m depth
\+ <100/ml maximum number
++ 100-500/ml maximum number
+++ 500-1500/ml maximum number
++++ >1500/ml maximum number

summer through autumn, compared to minimum values of 1-2 μg/liter observed from January through March.

Algae.—The pattern of algal succession in Shagawa Lake was a spring bloom of green algae followed by an early summer diatom bloom and blue-green bloom(s) during mid- to late summer (Fig. 4). The spring bloom of green algae was dominated by *Chlorella*-type algae in 1971 and by *Chlamydomonas* spp. in 1972. *Asterionella* spp. and *Fragilaria* spp. dominated the diatom bloom in 1971 and *Synedra* spp. in 1972. In 1971, the blue-green algal bloom was dominated by *Anabaena* spp. in June and *Aphanizomenon flos-aquae* in August. In 1972, the dominant blue-green algae were *Anabaena circinalis, A. spiroides* and *Coelosphaerium naegelianum* in early July, late July and late August, respectively. The maximum blue-green algal counts (numbers/ml) during these bloom periods were 2940 in August 1971 (80% *Aphanizomenon flos-aquae*), 1020 in early July 1972 (96% *Anabaena circinalis*) and 1120 in August 1972 (84% *Coelosphaerium naegelianum*).

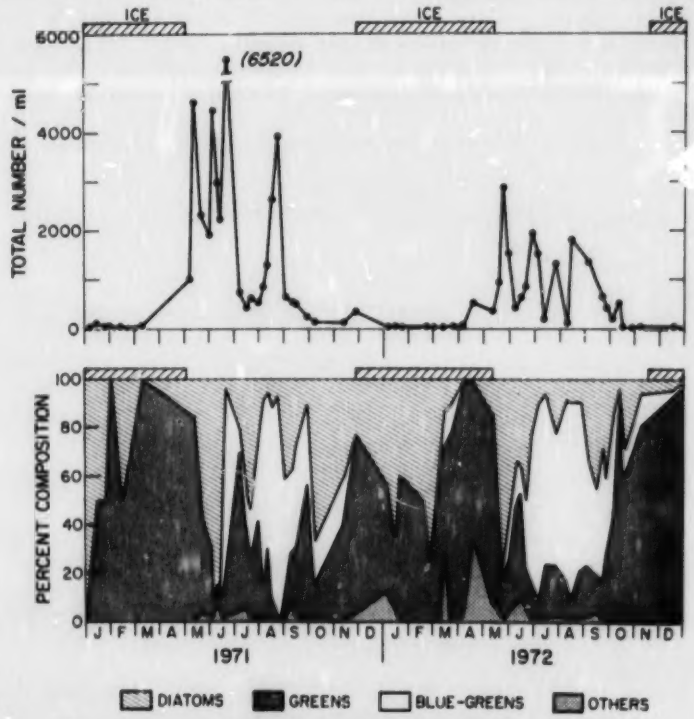

Fig. 4.—Shagawa Lake phytoplankton concentration and group composition at the 1.5-m depth for 1971, 1972

The algal community in Burntside Lake, much smaller than in Shagawa Lake, was dominated by diatoms and green algae (Fig. 5). During late summer 1972, 40-50% of the algal community consisted of blue-green, dominated by *Chroococcus* spp. and lesser amounts of *Oscillatoria* spp. and *Coelosphaerium naegelianum*. The most abundant diatoms were *Synedra* spp., *Rhizosolenia eriensis* and *Tabellaria* spp., and the most abundant green algae were *Trachelomonas* spp., *Chlamydonas* spp. and *Ankistrodesmus* spp. Table 4 shows the major phytoplankton found in Shagawa and Burntside lakes during 1971 and 1972.

Macrophytes.—Macrophytes were very sparse in both Shagawa and Burntside lakes and were scattered in narrow bands in the littoral (0-2 m depth) areas of shallow bays. P. Swain, University of Minnesota (pers. comm.), identified the dominant species in Shagawa Lake as bur reed (*Sparganium eurycarpum*), water lily (*Nuphar variegatum*), pondweed (*Potamogeton richardsonii*), waterweed (*Elodea canadensis*) and bushy pondweed (*Najas flexilis*). In 1968, the Minnesota Department of Conservation surveyed Burntside Lake and estimated that emergent vegetation covered about 0.1% of the lake surface area. These macrophytes included scattered growth of sedge (*Carex* spp.), water lily (*Nuphar variegatum* and *Nymphaea tuberosa*), bur reed (*Sparganium fluctuans*) and pondweed (*Potamogeton richardsonii* and *P. natans*).

Zooplankton.—Zooplankton was not sampled in Burntside Lake in

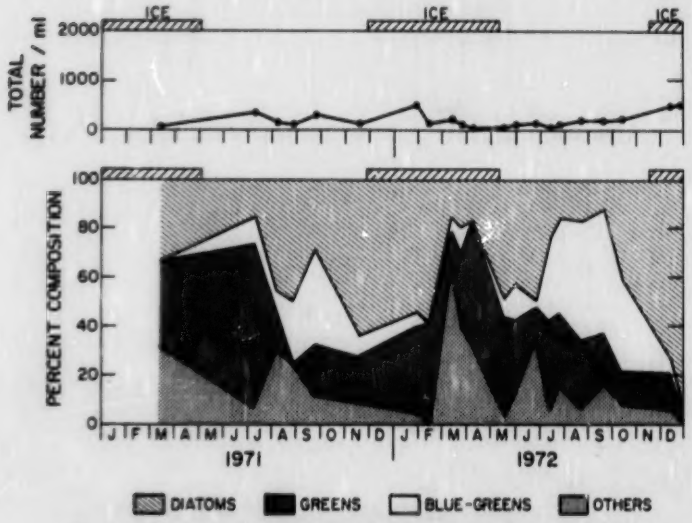

Fig. 5.—Burntside Lake phytoplankton concentration and group composition at the 1.5-m depth for 1971, 1972

1971; therefore, Figure 6 represents only 1972 data. Protozoans and rotifers, followed by copepods and cladocerans (Fig. 6A), were the most numerous zooplankton in Shagawa Lake. *Vorticella campanula* and *Epistyllis* spp. were dicyclic protozoans with population maxima occurring in June and December. *Keratella cochlearis* dominated the rotifers, with population maxima occurring in July and October, while maximum populations of *Polyarthra vulgaris* occurred in June. Other numerically important rotifers included *Keratella quadrata, Asplanchna* spp. and *Kellicottia longispina*. Predominant copepods were nauplii and *Cyclops*-types (population maxima occurring in December), followed by smaller numbers of *Diaptomus* spp. Samplings in later summer detected a few *Chaoborus* spp.

In Burntside Lake, the copepods generally were most abundant throughout the year, followed by rotifers, protozoans and minor amounts of cladocerans (Fig. 6B). Nauplii, *Cyclops*-types and *Diaptomus* spp. dominated the copepods with population maxima in June. The

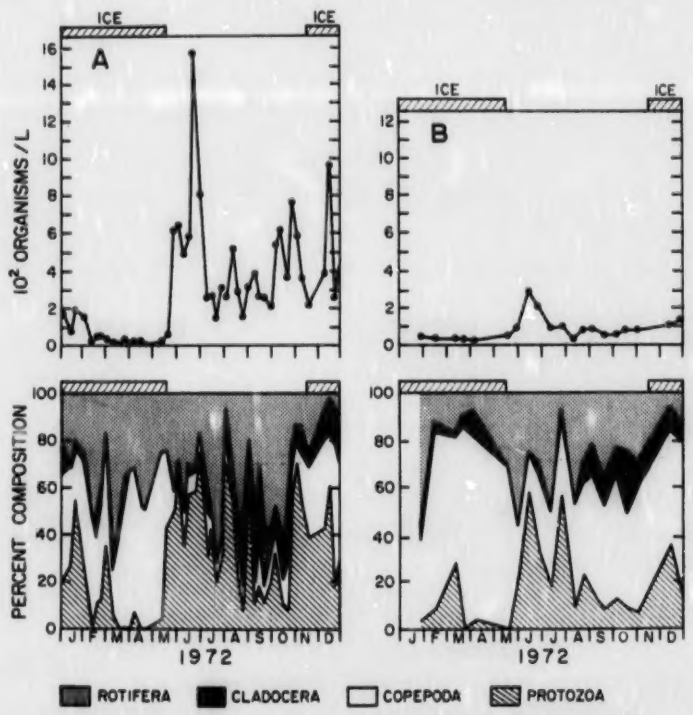

Fig. 6.—Zooplankton concentration and group composition for 1972. (A) Shagawa Lake; (B) Burntside Lake

dicyclic protozoans, *Vorticella* and *Epistylis*, reached population maxima in June and December. *Bosmina* sp., most abundant in November and December, dominated the cladocerans. Minor numbers of *Chydorus sphaericus* and *Daphnia galeata mendotae* also occurred. Dominant rotifers were *Keratella cochlearis*, *Conochiloides lossuarius* and lesser numbers of *Kellicottia longispina*, *Asplancha* spp. and *Polyarthra vulgaris*. All had population maxima in June except *Asplancha* spp. which peaked in July.

Benthic fauna.—Sampling of benthic fauna in Burntside Lake did not begin until 1973; therefore, only that year is used in comparing the two lakes even though the tertiary treatment plant began operating at Shagawa Lake early that year (Fig. 7). Notably, however, limnological data in Shagawa Lake during the 1st 9 months of 1973 were similar to earlier years.

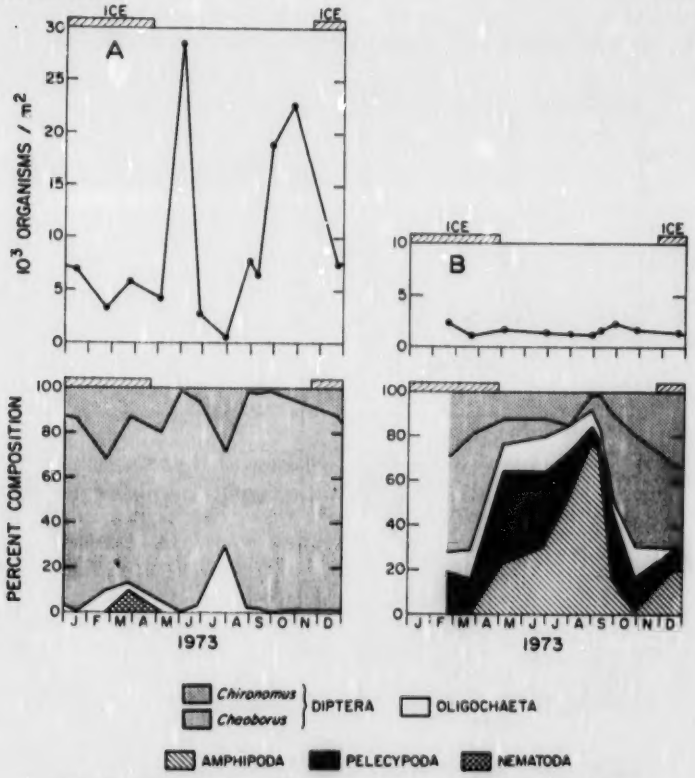

Fig. 7.—Benthos concentration and group composition for 1973. (A) Shagawa Lake; (B) Burntside Lake

The benthic organisms in Shagawa Lake reached maximum populations of about 29 × $10^3/m^2$ and 23 × $10^3/m^2$ in June and late October, respectively (Fig. 7A). More than 90% of these organisms were *Chaoborus* spp. In contrast, Burntside Lake had benthic populations ranging from 1100 to 2400/m^2, with diptera (predominantly *Chaoborus* spp.) comprising about 45% during the winter and less than 10% in the summer (Fig. 7B). The *Palpomyia* group was found in Shagawa Lake but not in Burntside Lake. *Chironomus plumosus* represented the chironomids in Shagawa Lake, with a maximum population of about 1000/m^2 in midwinter. The chironomids, *Tribelos* sp. and *Microspectra* spp., were observed in Burntside Lake but not in Shagawa.

In Shagawa Lake, nematodes were found only in early spring, reaching a maximum population of 470/m^2. Oligochaetes averaged about 140/m^2 throughout the year. Oligochaetes in Burntside Lake generally numbered about 200/m^2 all year. In late August, amphipods (the predominant organism tentatively identified as *Crangonyx* sp.) accounted for 77% of the benthos. Pelecypods (*Pisidium* spp.) reached a maximum in early May at 640/m^2, accounting for 38% of the total benthic organisms in the Burntside sample.

DISCUSSION

The limnological comparison of Shagawa and Burntside lakes showed the effects of basin morphology and 70 years of nutrient enrichment with domestic waste water on water quality. The basins of Burntside and Shagawa lakes were formed by the retreat of the Wisconsin glacier approximately 10,000 years ago. Burntside's greater depth and surface area plus its low nutrient loading have permitted it to remain oligotrophic, while Shagawa Lake, because of its smaller volume and high nutrient loading, has aged more rapidly. According to paleolimnological studies (Bradbury and Waddington, 1973), Shagawa Lake was probably mesotrophic for at least 2000 years prior to the arrival of European settlers. Perhaps this was true because of its larger ratio of watershed area to lake volume than that of Burntside.

Vollenweider (1968) proposed a scheme for classifying the trophic status of lakes on the basis of specific loading rates of nitrogen and phosphorus normalized to mean lake depth and surface area. A lake with the mean depth of Shagawa Lake and specific loading rates exceeding 0.15 g P/m^2/year and 2.2 g N/m^2/year would likely be eutrophic provided no other nutrients or factors were limiting. Before the start-up of the tertiary waste-water treatment plant in 1973, the specific loading rates of Shagawa Lake were 0.73 g P/m^2/year and 7.64 g N/m^2/year. Burntside Lake, with estimated specific loadings of 0.04 g P/m^2/year and 2.0 g N/m^2/year, falls into the oligotrophic category.

The annual nitrogen to phosphorus ratio (N/P) by weight supplied from all inputs to Shagawa Lake was 10.5. The N/P ratio found in the

filterable material during the summer period was also 10.5. This suggests that primary production is essentially nitrogen-controlled, when compared with Vollenweider's N/P ratio of 14.7. This conclusion was supported by laboratory algal assays, and the lake is likely to favor nitrogen-fixing blue-green algae, which, in fact, it does. Another indication of nitrogen limitation is the decrease of inorganic nitrogen in the upper waters to undetectable values due to uptake into biomass. Algae during this period presumably obtained their required nitrogen from recycled nitrogen, nitrogen regenerated from the sediment or N_2 fixation. The nitrogen budget shows that nitrogen could have been generated within the lake (Malueg *et al.*, 1975), suggesting N_2 fixation. The blue-green algae in Shagawa Lake in late summer were capable of fixing nitrogen for their nutrient needs and probably did so. The estimated N/P ratio supplied to Burntside Lake was about 50, which suggests a phosphorus-controlled system.

The breakup of the summer thermocline in Shagawa Lake during storms is an important factor in allowing periodic epilimnetic nutrient enrichment of nutrients generated in the hypolimnion, thus helping maintain the high summer algal biomass levels. Similar observations were noted in Lake Mendota, Wisconsin, by Stauffer and Lee (1973).

The composition of the summer phytoplankton in Shagawa Lake was characteristic of a eutrophic system (Rawson, 1956). It was predominantly cyanophycean, supporting large populations of *Anabaena, Aphanizomenon, Coelosphaerium* and others; in addition, high numbers of *Asterionella, Fragilaria* and *Stephanodiscus* were also seen. The summer phytoplankton genera present in Burntside Lake were not altogether in accordance with generally accepted notions concerning oligotrophic lakes. In 1972, while expected indicators such as *Tabellaria* and *Dinobryon* were present in conspicuous numbers, approximately 50% of the algae in late summer were blue-greens with *Chroococcum, Coelosphaerium* and *Oscillatoria* dominating. Rawson (1956) points out that such situations are not particularly unusual for oligotrophic lakes and considers a number of explanations.

The benthic fauna of the deep water sediments appear to be very sensitive to trophic levels. The outstanding difference between the two lakes was the dominance of *Chaoborus* in Shagawa Lake. The high number of *Chironomus* found in Shagawa Lake also indicates its eutrophic condition (Brinkhurst, 1969). Moreover, *Microspectra*—observed in oligotrophic or mesotrophic Swedish lakes (Wiederholm, 1973)—was found in Burntside Lake sediment, but not in Shagawa Lake.

Differences were noted in the fisheries of the lakes by the Minnesota Department of Conservation. In a survey conducted in 1967 and 1968, three times more fish were caught with nets and traps in Shagawa Lake than in Burntside Lake (Minnesota Department of Conservation, 1968). In Shagawa Lake, cisco (*Coregonus artedii*) and walleye (*Stizostedion vitreum*) accounted for 33% and 28%, respectively, of the deep-water catch. The catch netted about three times more cisco and

two times more walleye than the 1968 average in the local area. In Burntside Lake, the dominant species (48%) caught in the deep-water gill nets was the lake whitefish (*Coregonus clupeaformis*), a catch about seven times the local average (Minnesota Department of Conservation, 1968). In Shagawa Lake, yellow perch *(Perca flavescens)* accounted for 26% of the catch in shoal areas while rock bass *(Ambloplites rupestris)* dominated (59%) the shoal area catch in Burntside Lake.

Twenty-five species of fish were captured in the netting and shoal-seining of Burntside Lake. All those species except cisco and lake trout *(Salvelinus namaycush)* were common to the area; however, most lakes in the area had less than half this number of species. Seventeen species were captured in Shagawa Lake. Paetz and Zelt (1974) likewise observed a greater number of species in an oligotrophic lake in northern Alberta, Canada, when compared to a eutrophic lake in the approximate area. They did not observe cisco and walleye in the eutrophic lake they evaluated. It is interesting to note, however, that these species were the most abundant in eutrophic Shagawa Lake.

Other physical and chemical differences of the two lakes typify comparison of eutrophic and oligotrophic lakes. For example, during the summer Shagawa Lake exhibited high *p*H, anaerobic deep water, large variations in phosphorus and nitrogen concentrations with depth and low Secchi disc values. Burntside Lake, however, showed only slight fluctuations in chemical and physical parameters throughout the year.

Shagawa Lake has changed physically, chemically and biologically during the past 70 years as a result of high nutrient loading from domestic waste water. With the recent processing of waste water to reduce the phosphorus loading to the lake by 70-80%, the lake is in a period of phosphorus washout and, consequently, should be reversing its trophic condition towards the mesotrophic level. Limnological observations will continue over the next few years to determine which constituents are influenced and at what rate.

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